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# EFFECTS OF ACUTE DEHYDRATION AND STARVATION ON MUSCULAR STRENGTH AND ENDURANCE

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*Bosco, J. S., Greenleaf, J. E., Bernauer, E. M.* and *Card, D. H.* Effects of acute dehydration and starvation on muscular strength and endurance. Acta Physiol. Pol. 1974, 25 (5): 411—421. Maximal isometric muscular strength of elbow flexion, shoulder extension and knee extension (cable tensiometer) and muscular endurance (ergometer tolerance at 1,400 kpm/min and timed sit-ups) were measured in 21 men, ages 21—30, before and after a 3-day experimental period. One group served as *ad libitum* control, the second underwent water restriction of 1,066 ml/day and the third group had no food or water (total starvation). A controlled, high protein diet (2,887 kcal/day) was utilized to accentuate urinary water loss. Mean total body wt decreased 5.7% ($P < 0.05$) in the dehydration group (DG), 5.8% ($P < 0.05$) in the starvation group (SG) and 1.5% (n. s.) in the control group (CG). Mean body strength losses were: control — 7.5%, dehydration — 10.4% and starvation — 9.7%. Mean left elbow flexion strength was reduced 13.4% ($P < 0.05$) in the (CG) and 16.6% ($P < 0.05$) in the (DG); right knee extension strength was reduced 12.6% ($P < 0.05$) with starvation. Endurance to sit-ups decreased 9% ($P < 0.05$) with (D) and 13% ($P < 0.05$) with (S). The dehydration and starvation states could be distinguished from control by similar increases in serum creatinine, urinary K and urinary osmolarity; and decreases in body wt, plasma vol, urinary min vol, and creatinine clearance. Changes unique to (S) were increased urinary creatinine, decreased serum glucose and decreased urinary Cl. Only elevated serum osmolarity with (D) separated it from (S) and (C). With (D), the decreased strength and endurance is attributed to water loss and electrolyte shifts. The greater loss of strength and endurance with (S) is attributed to water and electrolyte losses, especially K, plus the reduction in serum glucose concentration.

Muscular strength, involving the use of large muscle groups, is primary constituent for optional work performance. Acute, moderate dehydration induced by moderated heat and/or exercise that results in 5% body wt loss does not change maximal oxygen uptake ($\dot{V}_{O2}$) while working in

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a cool environment, but it does impair maximal work endurance 20 to 45% [19, 20]. Exercise in the heat with accompanying sweat loss can reduce maximal oxygen uptake by 27% and submaximal endurance by 48% [8]; the mechanisms are largely unknown. With *ad libitum* water consumption previous observations indicate that maximal isometric strength is not reduced until the body weight loss reaches 10% in acute semi-starvation [22], in chronic semi-starvation [14] and in acute total starvation [6, 21]. Since starvation is usually accompanied by dehydration [23], it is difficult to determine if loss of strength is due primarily to dehydration, caloric deficit, or both. There is no general agreement whether moderate dehydration reduces maximal isometric muscular strength in subjects with normal caloric intakes: some authors have reported little or no change [12, 19] while the results of other studies have indicated decreases in strength of 7% to 10% [3, 13].

In view of these conflicting results, the present study was undertaken (a) to determine if dehydration and starvation cause a loss of maximal isometric strength and muscular endurance; and (b) to attempt to seperate the effects of total starvation from dehydration.

## PROCEDURES AND METHODS

Twenty-one healthy college men, ages 21—30, participated in a 15-day experiment. They were palced into three groups: (a) control (CG), (b) dehydration (DG); and (c) starvation (SG). The average age, height and weight for each group was approximately equal

*Table 1.* Anthropometric and biochemical* baseline data
The total experiment consisted of a 4-day controlled dietary adjustment period

| | Age, | Ht, | Wt, | Serum Glucose, | Serum Uric Acid, | Blood Urea $N_2$, | Hb, | ESR, | PCV, | WBC X $10^{-3}$, |
|---|---|---|---|---|---|---|---|---|---|---|
| | yr | cm | kg | mg/100 ml | mg/100 ml | mg/100 ml | g | mm | mm | no. |
| Control group | | | | | | | | | | |
| $\bar{X}$ | 23 | 179 | 78.25 | 87 | 5.9 | 13.6 | 15.1 | 5 | 45 | 5.4 |
| ± SD | 2 | 9 | 7.94 | 12 | .8 | 1.1 | .7 | 3 | 1 | .9 |
| Dehydration group | | | | | | | | | | |
| $\bar{X}$ | 24 | 178 | 77.18 | 90 | 6.7 | 13.2 | 14.6 | 5 | 45 | 5.2 |
| ± SD | 4 | 8 | 6.66 | 8 | 2.2 | 1.0 | .6 | 4 | 2 | .8 |
| Starvation group | | | | | | | | | | |
| $\bar{X}$ | 24 | 180 | 77.22 | 89 | 6.1 | 13.7 | 15.2 | 3 | 45 | 5.4 |
| ± SD | 2 | 5 | 5.34 | 11 | .9 | 3.0 | .8 | 3 | 2 | 1.1 |

*Table 2.* Dietary composition and daily intake

| Group | Calories | Protein | CHO | Fat | Na | NaCl | $H_2O$ (Food) | $H_2O$ (Met) | $H_2O$ (Liquid Intake) | $H_2O$ (Total) |
|---|---|---|---|---|---|---|---|---|---|---|
| | kcal | g | g | g | g | g | g | g | ml | ml |
| Control | 2,887 | 299 (43%) | 376 (54%) | 22 (3%) | 3.5 | 8.9 | 700 | 166 | AD LIB. | 2,866 |
| Dehydration | 2,887 | 299 (43%) | 376 (54%) | 22 (3%) | 3.5 | 8.9 | 700 | 166 | 200 | 1,066 |
| Starvation | No food or water | | | | | | | | | |

followed by a return to their *ad libitum* dietary intake for 5 days, then a 3-day experimental period, and finally 3 days of recovery (Figure 1).

During the controlled dietary adjustment period (days 1—4) all subjects were placed on a high protein, low fat, semi-liquid diet composed of Sustagen (Mead-Johnson), Gevral-protein (Lederle) and bouillon cubes (Wylers) (Table 2). The purpose of the high protein diet was to accentuate dehydration by increased urinary loss. The subjects returned to their normal diets on days 5 through 9 and then began their 3-day experimental diets (days 10—12). The (DG) consumed 2,887 kcal and 8.9 g NaCl per day and their average total daily water intake, including metabolic water, was 1,066 ml/day. The (SG) had no food or water. During the recovery period (days 13—15) the subjects again returned to their normal *ad libitum* diets. On days 1, 3, 5, 7, and 9 all subjects participated in a onehalf hour period of running and muscular endurance exercises designed to stabilize their physical condition.

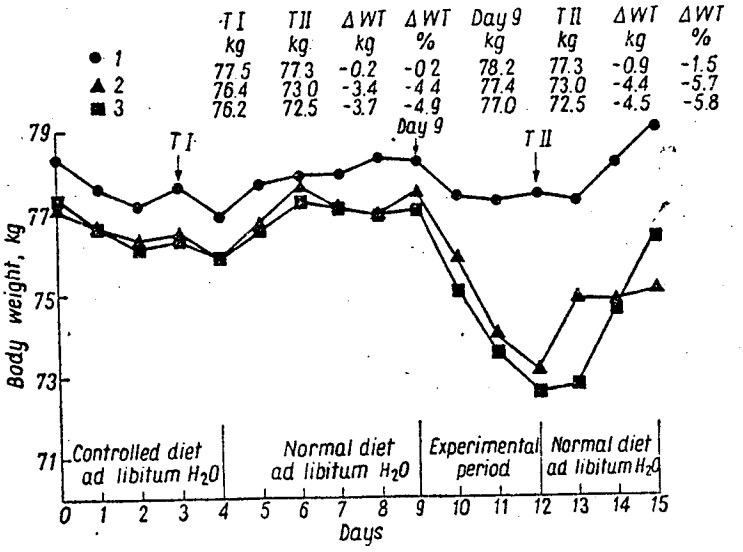


*Fig. 1.* Mean body weights for the three groups during the 15 day experiment. *1* — Control group; *2* — Dehydration group; *3* — Starvation group.

During the experimental period the (D) and (S) groups were housed in the laboratory under constant supervision while the (CG) continued its normal mode of living, except for the controlled diet. All subjects slept overnight in the laboratory before Test I and Test II (Figure 1).

Nude (post-absorptive) body wt was measured daily on a balance accurate to ±5 g. Maximal isometric muscular strength of elbow flexion and shoulder and knee extension, taken on both right and left extremities, was measured with a tensiometer; reliability coefficients for these measures range from 0.80 to 0.97 [5]. Leg endurance was measured with an electronically-braked Collins (Mark III) bicycle ergometer [4]. The subjects rode the bicycle at a work load of 1,400 kpm/min (50—60 rpm) to exhaustion or for five minutes. Endurance of the abdominal musculature was the maximum number of sit-ups performed in two minutes [26].

Evans Blue space (plasma volume) was measured with one 10-min post injection blood sample [17]; a correction of 0.96 was made for trapped plasma in the micro-hematocrit determination on venous blood [15]. Red cell volume was calculated from the total blood volume minus plasma volume. The following variables were also measured: serum and urinary sodium and potassium (Baird flamephotometer, Model KY-2), chloride [7], endogenous creatinine [2], and total osmolarity (Fiske osmometer, Mark III), serum glucose [24] and urinary total nitrogen (micro-Dumas method — Coleman Model 20 nitrogen analyzer). Insensible water loss was calculated as overnight body wt loss minus ($CO_2$—$O_2$). The ($CO_2$—$O_2$) values were the average of the measurements taken just before retiring and the basal values the following morning.

A one-way analysis of variance [10, 11] was used to evaluate differences between groups during Test I, the differences within groups between Test I and Test II, and the differences between groups during Test II. The level of statistical significance was $p < 0.05$ and nonsignificant differences were indicated by n. s.

## RESULTS

Inspection of the data in Tables 1 and 3 indicated that the subjects were essentially similar in most baseline biochemical variables.

Weight and water exchange. Average body wt decreased significantly (TII-TI) in both the dehydration (−3.37 kg; 4.4%) and starvation (−3.72 kg; 4.9%) groups (Figure 1). A TII-TI comparison eliminates the influence of the wt loss due to the controlled diet. The high protein low fat diet (Table 2), fed to all subjects during the equilibration period (Day 0 to Day 3), resulted in an average reduction in body wt of about 1 kg in all three groups (Fig. 1). These dietary losses were included when comparing wt losses at the end of the experimental period (TIII) with body wt levels during the normal, *ad libitum* diet (Day 9). Average wt loss in the (CG) was 0.9 kg (1.5%); and after (D) −4.4 kg (5.7%). The wt loss in the (SG) was −4.5 kg (5.8%), very similar to the values.

Compared with control values (TI), insensible water loss in the experimental period (TII) decreased 19.8% (n.s.) in the (CG); 18.8% ($P < 0.05$) in the (DG); and only 3.2% (n.s.) in the (SG) (Table 3).

*Blood variables.* During the experimental period plasma volume (PV)

*Table 3.* Average (±SD) values for blood, urinary and strength measures for the three groups on Test I (Day 3) and Test II (Day 12)

| | | Control group | | | | Dehydration group | | | | Starvation group | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TI | ±SD | TII | ±SD | TI | ±SD | TII | ±SD | TI | ±SD | TII | ±SD |
| Serum Na | mEq/l | 137.8 | 8.4 | 143.1 | 4.8 | 139.8 | 9.0 | 147.6 | 3.1 | 139.6 | 6.9 | 142.9 | 6.5 |
| Serum K | mEq/l | 4.5 | .5 | 4.8 | .6 | 4.3 | .4 | 4.4 | .4 | 4.2 | .6 | 4.0 | .5 |
| Serum Cl | mEq/l | 103.3 | 5.0 | 101.8 | 4.0 | 104.7 | 2.5 | 103.6 | 3.9 | 102.4 | 3.9 | 101.5 | 2.9 |
| Serum Osm. | mOsm/l | 279.7 | 7.6 | 276.7 | 4.7 | 281.1 | 7.6 | 290.3 | 7.9 | 277.4 | 6.5 | 280.0 | 6.7 |
| Serum Glucose | mg/100 ml | 77.9 | 7.7 | 79.2 | 4. | 78.1 | 6.6 | 79.5 | 4.6 | 80.6 | 6.1 | 62.0 | 10.3 |
| Serum Creat. | mg/100 ml | .94 | .05 | .94 | .07 | .92 | .10 | .99 | .13 | .92 | .10 | 1.04 | .09 |
| Plasma Vol. | ml | 3732. | 535. | 3816. | 836. | 3679. | 719. | 3186. | 273. | 3954. | 234. | 3328. | 578. |
| Red-Cell Vol. | ml | 2966. | 411. | 3276. | 591. | 3033. | 618. | 3199. | 295. | 3105. | 324. | 3266. | 522. |
| Hematocrit | % | 46.2 | 1.5 | 48.3 | 1.5 | 47.0 | 2.0 | 51.7 | 1.4 | 45.7 | 2.3 | 51.6 | 2.3 |
| Blood Vol. | ml | 6698. | 926. | 7092. | 1413. | 6712. | 1307. | 6386. | 538. | 7059. | 494. | 6594. | 1065. |
| Urinary Na | mEq/l | 71.7 | 16.9 | 38.1 | 11.6 | 74.6 | 22.6 | 45.3 | 20.9 | 65.8 | 7.1 | 36.7 | 22.9 |
| Urinary K | mEq/l | 23.5 | 8.5 | 26.8 | 11.8 | 35.4 | 29.8 | 79.4 | 32.9 | 23.1 | 9.4 | 63.1 | 22.4 |
| Urinary Cl | mEq/l | 88.3 | 17.4 | 76.3 | 26.6 | 99.8 | 48.2 | 93.6 | 12.3 | 81.4 | 17.3 | 45.5 | 14.4 |
| Urinary Osm. | mOsm/l | 1085. | 73. | 1128. | 116. | 1059. | 151. | 1282. | 139. | 1058. | 160. | 1263. | 133. |
| Urinary $N_2$ | % | 2.26 | .27 | 2.40 | .40 | 2.27 | .35 | 2.52 | .29 | 2.10 | .37 | 2.58 | .35 |
| Urinary Creat. | mg/100 ml | 131.6 | 28.1 | 134.0 | 24.4 | 118.5 | 25.2 | 163.5 | 53.6 | 137.4 | 38.9 | 315.8 | 24.9 |
| Urinary Min. Vol. | ml/min | .85 | .25 | 1.01 | .23 | 1.18 | .21 | .78 | .17 | .91 | .32 | .39 | .09 |
| Creat. Clear. | ml/min | 116.9 | 30.7 | 141.4 | 28.1 | 150.4 | 42.0 | 122.4 | 10.4 | 127.3 | 25.5 | 116.5 | 20.8 |
| Insensible $H_2O$ | g/(hr · m²) | 20.2 | 6.5 | 16. | 2.7 | 20.2 | 3.1 | 16.4 | 3.2 | 18.7 | 3.1 | 18.1 | 5.6 |
| (R) Shoulder Extension | kg | 76.7 | 17.0 | 68.5 | 10.2 | 67.6 | 11.1 | 64.8 | 11.5 | 69.5 | 10.5 | 60.7 | 4.0 |
| (L) Shoulder Extension | kg | 71.7 | 12.3 | 67.7 | 11.3 | 70.6 | 10.2 | 62.0 | 6.0 | 65.1 | 8.1 | 60.0 | 2.3 |
| (R) Elbow Flexion | kg | 78.7 | 14.6 | 76.0 | 6.9 | 74.1 | 14.4 | 70.4 | 14.4 | 76.3 | 15.4 | 71.1 | 14.8 |
| (L) Elbow Flexion | kg | 77.7 | 9.4 | 67.3 | 9.4 | 78.2 | 13.3 | 65.2 | 9.7 | 73.1 | 11.6 | 70.3 | 12.3 |
| (R) Knee Extension | kg | 92.3 | 12.2 | 87.0 | 14.2 | 100.4 | 21.0 | 86.0 | 17.0 | 94.0 | 14.7 | 82.1 | 12.2 |
| (L) Knee Extension | kg | 87.2 | 17.0 | 81.9 | 16.1 | 100.7 | 21.0 | 89.7 | 18.2 | 90.1 | 9.7 | 77.3 | 11.3 |
| Sit-ups | no./2 min | 57. | 13. | 67. | 19. | 58. | 6. | 61. | 7. | 64. | 10. | 62. | 12. |
| Body wt. | kg | 77.48 | 8.31 | 77.31 | 6.59 | 76.40 | 6.40 | 73.03 | 6.38 | 76.21 | 5.71 | 72.49 | 5.79 |

decreased from an average control level of 3,679 to 3,186 ml ($\Delta$ 13.4%, n.s.) in the (DG) and from 3,954 ml to a TII level of 3,328 ml ($\Delta$ 15.8%, $P < 0.025$) in the (SG) (Table 3). The average PV of the (CG) increased 2.2%. The percentage decrease in PV was about three times as great as the percentage decrease in body wt in the (DG) ($\Delta$wt = 4.4%, $\Delta$PV = = 13.4%) and (SG) ($\Delta$wt = 4.9%, $\Delta$PV = 15.8%) indicating that the plasma suffers a disproportionally greater loss of volume than body mass.

*Table 4.* Variables that exhibited statistically significant differences between groups at the end of the experimental period (TII): (C) control, (D) dehydration, (S) starvation

| Variable | Groups | P ⩽ |
|---|---|---|
| Serum Osmolarity (mOsm/l) | C vs. D | .005 |
| | D vs. S | |
| Serum Glucose (mg/100 ml) | C vs. S | .001 |
| | D vs. S | |
| Urinary Minute Volume (ml/min) | C vs. S | .001 |
| | D vs. S | |
| Urinary Creatinine (mg/100 ml) | C vs. S | .001 |
| | D vs. S | |
| Urinary Potassium (mEq/l) | C vs. D | .001 |
| | C vs. S | |
| Urinary Chloride (mEq/l) | C vs. S | .001 |
| | D vs. S | |

Hematocrit increased ($P < 0.05$) in all three groups, with the largest increase (12.9%) in the (SG). Serum creatinine was elevated 7.6% ($P < 0.025$) with (D) and 13% ($P < 0.01$) with (S). Serum glucose concentration remained relatively unchanged in the (C) and (D) groups, but decreased from 80.6 to 62.0 mg/100 ml (23.1%, $P < 0.01$) in the (SG). The level of serum glucose in the (SG) at the end of the experimental period was significantly lower ($P < 0.001$) than the (C) and (D) groups concentrations (Table 4).

During the experimental period in the (C) and (S) groups serum osmolarity varied $\pm 3$ mOsm/1, but it increased 9.2 mOsm/1 (n.s.) in the (DG) (Table 3). Thus, (S) resulted in a normal serum osmotic concentration. The final value of 290.3 mOsm/1 in the (DG) was higher ($P < 0.025$) than that of the other groups (Table 4) and it was due mainly to the increased serum sodium concentration of 7.8 mEq/1. The serum K and Cl concentrations were essentially unchanged.

*Urinary variables.* Urinary minute volume decreased from 1.2 ml/min (TI) to 0.8 ml/min (TII) ($\Delta$ 33.9%, $P < 0.005$) in the (DG) and from

0.9 ml/min to 0.4 ml/min ($\Delta$ 57.5%, $P < 0.01$) in the (SG) (Table 3). Accompanying the reduced urinary volume, urinary osmolarity increased about 20% ($P < 0.05$) in both the (D) and (S) groups, urinary nitrogen was slightly elevated (n.s.) and creatinine excretion was elevated, particularly with (S) ($P < 0.05$). Urinary potassium concentration increased from 23.5 to 26.8 mEq/1 (n.s.) in the (DG) and from 23.1 to 63.1 mEq/1 ($P < 0.01$) in the (SG). The TII K concentrations in the (D) and (S) groups were both increased ($P < 0.001$) over the (CG), but were not significantly different from each other (Table 4).

Urinary sodium excretion decreased in the (CG) ($P < 0.005$), the (DG) (n.s.) and the (SG) ($P < 0.01$). Urinary chloride concentration was reduced slightly in the (C) and (D) groups but it dropped from 81.4 to 45.5 mEq/1 ($P < 0.001$) in the (SG) (Table 3). Creatinine clearance was significantly ($P < 0.05$) elevated in the (CG], but decreased (n.s.) in the other two groups.

Thus, the (S) and (D) states may be distinguished from the (C) state by changes in the following variables: serum creatinine, plasma volume, creatinine clearance, urinary minute volume, urinary osmolarity, urinary potassium and body wt; i.e., these variables change similarly with (D) and (S). The following variables serve to separate (S) from the (D) and (C) states; i.e., changes unique to (S): serum glucose, urinary Cl and urinary creatinine. Only serum osmolarity distinguishes the effects of (D) from those of (S) and (C).

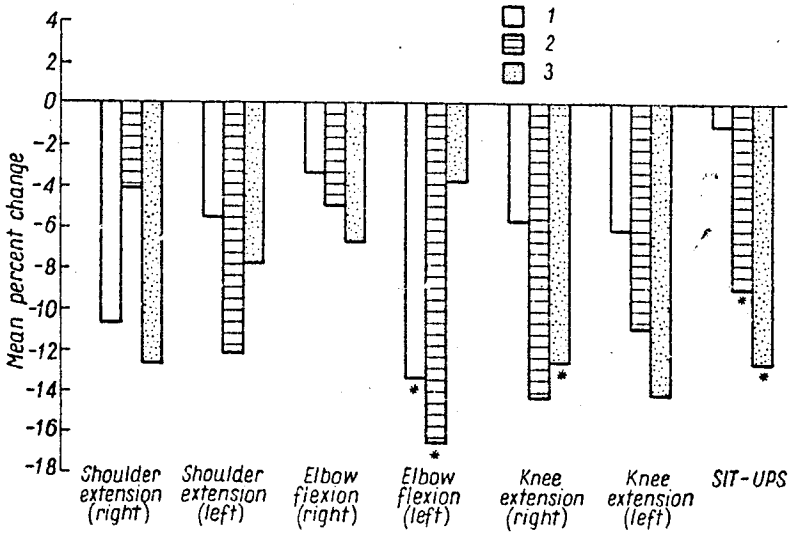


*Fig. 2.* Mean percent changes in maximal isometric strength and endurance (sit-ups) for each group: (TII-TI/TI) × 100. The asterisk indicates a significant change at the $P < 0.05$ level. *1* — Control group; *2* — Dehydration group; *3* — Starvation group.

*Maximal isometric strength and muscular endurance.* During the experimental period all strength measures decreased in all three groups (Fig. 2). The average strength losses (sum six % losses divided by six) were: (CG) 7.5%, (DG) 10.4%, and the (SG) 9.7%. In the (C) and (D) groups left elbow flexion strength decreased ($P < 0.05$) while right knee extension strength also decreased ($P < 0.05$) in the (SG). Apparently, the 3-day experimental period was not sufficiently long to distinguish between the effects of (D) and (S) on strength. In general, greater decrements in maximal isometric strength occurred in the (D) and (S) groups than in the (CG).

The number of sit-ups completed in 2 min decreased ($P < 0.05$) in the (D) and (S) groups (Fig. 2). The results of the bicycle ergometer test indicated that all 19 subjects were able to complete the test in the control (TI) experiment. In TII all six subjects in the (CG) completed the test, while only three of the dehydrated subjects and only two of the starved subjects were able to work at 1,400 kpm/min for five minutes. Thus, muscular endurance was reduced markedly with (D) and (S).

## DISCUSSION

The purpose of this study was to compare the effects of dehydration and total starvation on muscular strength and endurance.

The high protein diet was employed to accentuate urinary water loss [9, 18]. Only three subjects reported mild diarrhea on one or two occasions. Most subjects disliked the taste of the diet and made liberal use of various artificial flavorings.

During the experimental period the average compensated weight loss of 4.4 kg in the (DG) was about one kg greater than results from other studies that utilized similar dehydration regimens with more normal diets [1, 6]. The greater weight loss in the present study was no doubt due to the high protein diet. The average compensated wt loss of 4.5 kg in the (SG) was similar to the 4.1 kg loss reported by *Nadal* et al. [16] under similar conditions. Urinary and dermal water retention mechanisms conserved 2.3 kg in the (DG) and 2.3 in the (SG) (calculated from data in Table 3). If the urinary, sensible and insensible water losses of the control period continued unchecked during the experimental periods (uncompensated losses), the (DG) would have lost 5.4 kg and the (SG) 8.6 kg. Therefore, water retention accounted for the 1.0 kg difference (5.4 kg — 4.4 kg) between the uncompensated and compensated wt losses in the (DG), but for only slightly more than half of the 4.1 kg (8.6 kg — 4.5 kg) wt loss difference in the (SG). The residual wt loss in the latter group

was probably due to the combined wt (water) losses from increased tissue breakdown, suggested from greater urinary losses of nitrogen and creatinine, unreplaced fecal loss, and reduction in carbohydrate stores (serum glucose concentration reduced 23%) where 1 g of carbohydrate binds about 3 ml $H_2O$.

There is general agreement that dehydration reduces muscular endurance [8, 19]. The effect of dehydration upon maximal isometric strength is less certain. *Saltin* [19] found no change in elbow flexion and knee extension strength in men dehydrated acutely about 3% of their body wt by exposure to either a sauna bath or by exercise. *Greenleaf* et al. [12] also observed no change in hip and knee and trunk extension and hand grip strengths in men following chronic dehydration of 4.3% obtained by restricting water intake to 900 ml/day. The results of other studies have indicated that maximal isometric strength in women is reduced 7% to 19% following acute, moderate dehydration (3.3%) induced by exercise in the heat [13], and maximal strength is reduced up to 10% following 2.5% chronic dehydration in men [3]. In all the above investigations the subjects ate normal diets.

In studies with restricted caloric intakes but adequate water consumption, maximal strength was not affected below 10% body wt loss in neither acute and chronic semi-starvation [14, 21, 25]. Thus, restricted calories alone do not impair maximal isometric strength.

In spite of the loss of body water in the (D) and (S) groups and the reduction in body tissue and serum glucose concentration in the (SG), all three groups exhibited average body strength losses: (CG) −7.5%, (DG) −10.4% and −9% in the (SG). The loss of strength in the (CG) suggests an influence of the high protein diet. Other factors, such as motivation may be implicated, but it is important to note that all changes in strength were negative. We must therefore, conclude that dehydration and total starvation *per se* cause 2% to 3% reductions in average maximal strength. However, left elbow flexion strength was reduced significantly in the (CG) (13.4%) and in the (DG) (16.6%); right knee extension strength was reduced significantly in the (SG) (12.6%). Interestingly, in previous study [3] the only significant strength loss was in right elbow flexion (10.7%). While total strength seems slightly reduced, elbow flexion and knee extension strength are particularly susceptible to dehydration and starvation.

Optimal functioning of muscle requires adequate nervous stimuli, adequate neural transmitter substances and the ability of the muscle to respond to the efferent stimuli. Since average maximal strength was only slightly reduced, but endurance significantly reduced, one conclusion is that neuro-muscular impulse transmission and muscle response are not

compromised with moderate levels of dehydration and starvation. Endurance decrements must then be due to either a reduction in available energy for muscular contraction, influenced perhaps by impaired cardiovascular function due to dehydration, or possibly to a deterioration in impulse propagation due to altered ionic balance as the muscular contractions proceed. In spite of the decreased PV with starvation, the serum glucose concentration was reduced to 62 mg/100 ml from control levels of 81 mg/100 ml. This reduction could explain the diminished endurance with starvation.

However, serum glucose concentrations with dehydration (79.5 mg/100 ml) was unchanged from control levels while endurance was also reduced; thus, the hypoglycemia is not the major mechanism for the lower endurance with dehydration.

Increased creatinine excretion would indicate increased cellular breakdown, principally of muscle tissue. In the face of a decreased PV in the dehydration and starvation groups, normal serum potassium concentration was maintained but urinary potassium losses were increased markedly, also indicating increased cellular breakdown. The increased urinary potassium losses in the (DG) occurred even though there was adequate potassium intake from the diet. Serum sodium loss was reduced to aid in the maintenance of the PV. This reduction in sodium loss could have been caused by either a reduced glomerular filtration rate, as suggested from reduced creatinine clearances, by an increased reabsorption of sodium in response to the reduced plasma volume via stimulation of aldosterone, or both.

In summary, in both the (D) and (S) groups there was a marked body weight and plasma volume loss that caused water retention and electrolyte redistribution. The (DG), with their normal electrolyte and caloric input and a high protein intake, exhibited less severe cellular breakdown and a higher serum osmolarity than the (SG) even though the latter had a greater loss of PV. Plasma glucose concentration was decreased only in the (SG). There were somewhat greater decrements in strength and endurance with starvation compared with dehydration. Dehydration and total starvation that resulted in less than 6% total body weight losses led to (a) 2% to 3% decreases in average maximal isometric muscular strength; (b) up to 16% decreases in strength of specific muscle groups (elbow flexion and knee of extension); and (c) a significant decrease in muscular endurance. The decreased strength and endurance in the (DG) is attributed to electrolyte shifts and to the absolute loss of water. The greater loss of strength and endurance in the (SG) is attributed to the dehydration and electrolyte shifts, especially the large potassium loss, plus the reduction in serum glucose concentration.

## REFERENCES


1. *Black, D. A. K., McCance, R. A., Young, W. F.:* J. Physiol. 1944, 102, 406.
2. *Bonsnes, R. W., Taussky, H. H.:* J. Biol. Chem. 1945, 158, 581.
3. *Bosco, J. S., Terjung, R. L., Greenleaf, J. E.:* J. Sports Med. Physical Fitness 1968, 8, 81.
4. *Clark, J. H., Greenleaf, J. E.:* J. Appl. Physiol. 1971, 30, 440.
5. *Clarke, H. H., Bailey, T. L., Shay, C. T.:* Res. Quart. 1952, 23, 136.
6. *Consolazio, C. F., Nelson, R. A., Johnson, H. L., Matoush, L. O., Krzywicki, H. J., Isaac, G. J.:* Am. J. Clin. Nutr. 1967, 20, 684.
7. *Cotlove, E., Trantham, H. V., Bowman, R.:* J. Lab. Clin. Med. 1958, 51, 461.
8. *Craig, F. N., Cummings, E. G.:* J. Appl. Physiol. 1966, 21, 670.
9. *Danowski, T. S., Elkinton, J. R., Winkler, A. W.:* J. Clin. Invest. 1944, 23, 816.
10. *Dixon, W. J.* (ed.): Biochemical Computer Programs. Health Sciences Computing Facility, School of Medicine, University of California, Los Angeles, 1964.
11. *Duncan, D. B.:* Biometrics 1955, 11, 1.
12. *Greenleaf, J. E., Matter, M., Jr., Bosco, J. S., Douglas, L. G., Averkin, E. G.:* Aerospace Med. 1966, 37, 34.
13. *Greenleaf, J. E., Prange, E. M., Averkin, E. G.:* J. Appl. Physiol. 1967, 22, 55.
14. *Keys, A., Brozek, J., Henschel, A., Mickelsen, O., Taylor, H. L.:* Human Starvation. 1951, University of Minnesota Press, Minneapolis.
15. *McGovern, J. J., Jones, A. R., Steinberg, A. G.:* New. Eng. J. Med. 1955, 253, 308.
16. *Nadal, J. W., Pedersen, S., Maddock, W. G.:* J. Clin. Invest. 1941, 20, 691.
17. *Porat, von B. T. D.:* Acta Med. Scand. 1951, suppl. 265, 1.
18. *Quinn, M., Kleeman, C. R., Bass, D. E., Henschel, A.:* Metabolism 1954, 3, 49.
19. *Saltin, B.:* J. Appl. Physiol. 1964a, 19, 1114.
20. *Saltin, B.:* J. Appl. Physiol. 1964b, 19, 1125.
21. *Taylor, H. L., Brozek, J., Henschel, A., Mickelsen, O., Keys, A.:* Am. J. Physiol. 1945, 143, 148.
22. *Taylor, H. L., Buskirk, E. R., Brozek, J., Anderson, J. T., Grande, F.:* J. Appl. Physiol. 1957, 10, 421.
23. *Taylor, H. L., Henschel, A., Mickelsen, O., Keys, A.:* J. Appl. Physiol. 1954, 6, 613.
24. *Teller, J. B.:* Am. Chem. Soc. 1956, Abstract 155, 69c.
25. *Tuttle, W. W.:* Research Quart. 1943, 14, 158.
26. *Wedemeyer, R. A.:* Research Quart. 1946, 17, 40.


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